# Appendix B

# Heat-flux sensor - Sample Calibration Report

# REPORT OF CALIBRATION

35070S Special Test of Heat Flux Sensor

for

HF Sensors, Model # HFT-X-00000J
Serial # 00000, 11111, 22222, 33333, 44444, and 55555

Submitted by:

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(See your purchase order 0446N, dated June 10, 1999)

**1. Description of Calibration Item(s)**

Six Schmidt-Boelter type heat flux sensors were calibrated by the National Institute of Standards and Technology (NIST) from 0 W/cm$^2$ to 5 W/cm$^2$. The Schmidt-Boelter sensor measures the temperature difference between two parallel surfaces normal to the incident heat flux. The thermopile concept is used to make accurate measurement of the temperature gradient across a thin thermally insulating material to determine the heat flux rate to the sensor surface. The test sensors were of miniature type (4 mm body diameter), and the design total (radiant and convective) heat flux range is 5 W/cm$^2$ ). Appendix A lists major specifications of the sensors.

Sensor # 11111 showed an open circuit for the body temperature thermocouple leads. This sensor was calibrated without monitoring the sensor body temperature.

**2. Description of Calibration**

The heat flux sensors were calibrated using the 25-mm Variable Temperature Blackbody (VTBB) as a transfer source. A room-temperature water-cooled electrical substitution radiometer (ESR) was used as a transfer standard. The ESR is a Kendall radiometer model Mark IV self-calibrated at a power level of 920 mW. The cooling water flow rate and temperature were 0.9 L/m and 24 °C, respectively.

Laboratory Environment
 Temperature: 23 °C ± 2 °C
 Relative Humidity: 50 % ± 3 %

SAMPLE

Calibration Date: August 19, 1999
NIST Test No.: 844/000000-99

| **Appendix A: Details of Test Schmidt-Boelter Sensors** | |
|---|---|
| **Manufacturer** | HF_Sensors Corporation |
| **Number of Gages** | 6 |
| **Gage specification** | HFT-X-00000J |
| **Gage identification** | Serial # 00000, 11111, 22222, 33333, 44444 and 55555 |
| **Design Heat Flux** | 5 W/cm$^2$ |
| **Body diameter** | 4 |
| **Body length** | 8 |
| **Sensor area** | 1 mm x 1 mm |
| **Thermopile lead wires** | 32 AWG, Stranded copper with Teflon insulation twisted pair. (White positive, Black negative) |
| **Body-temperature thermocouple** | Type J (Iron-Constantan), 30 AWG |
| **Maximum body-temperature** | 204 °C (400 °F) |

| **Appendix B: Schmidt-Boelter Sensors Calibration in VTBB** | |
|---|---|
| **VTBB** | Thermogage Furnace<br>25 mm diameter cavity (with short extension piece) |
| **Temperature range** | 1300 °C to 2330 °C |
| **Transfer standard** | Electrical Substitution Radiometer, Mark IV<br>Serial No.: 47601, Control Unit Serial No.: 17601<br>Manufacturer: TMI, La Canada, CA<br>Self-calibration Power Level: 920 mW |
| **Sensor location** | On the VTBB cavity axis (1.27 cm from the exit)<br>Located using a gage block.<br>Distance from aperture: 10.7 cm |
| **Calibration type** | For incident flux<br>Up to about 5.0 W/cm$^2$ at the sensor surface,<br>Measured ESR reading used for transferring heat flux |
| **Body temperature** | Monitored using a Fluke thermometer |
| **Other accessories** | Cooling water flow rate for ESR: 0.9 L/min<br>Cooling water temperature: 24 °C<br>ESR and Sensor thermopile outputs acquired using a<br>HP3857A Digital Voltmeter triggered by Pentium computer. |

SAMPLE

The sensors were mounted on a holder/heat-sink for purposes of testing. The ESR and the sensors were located at a fixed distance from the VTBB exit using a standard gage block (1.27 cm thick); corresponding to a distance of 10.7 cm from the end of the blackbody heated region. The variation in the heat flux level at the ESR/sensor location was obtained by operating the VTBB at different temperatures in the range 1573 K to 2603 K.

The output of the ESR (W/cm$^2$) and the sensors (mV) were recorded by positioning the VTBB, after stabilization of the set temperature, in front of the instruments. Appendix B gives details of the various parameters relevant to this calibration. The ESR readings were recorded after about 60 s exposure to the radiant heat flux to account for the long time-constant. The Schmidt-Boelter sensors outputs were recorded for about 20 s to 40 s depending on the heat flux level. The sensor body-temperature was monitored using a Fluke thermometer during exposure to the radiant flux. The maximum rise in the gage body temperature was less than 20 K at the highest heat flux level.

Before calibrating the test sensors, a reference Schmidt-Boelter type sensor was calibrated. This reference sensor is frequently calibrated to monitor the long-term repeatability of the calibration procedure. The measured responsivity from the check calibration agreed with the mean of previous calibrations within 1.0 %.

## 3. Results of Calibration

Tables 1a and 1b give the measured output of the sensors for different heat flux levels at the sensor surface. Over the heat flux range tested, the outputs of all the six sensors increased linearly with increasing heat flux. Linear curve fit to the test data showed the calculated regression factor was 1.000 for all the sensors. Figures 1a and 1b show the results of calibration along with the linear regression analysis to the measured data. The responsivity and scale factor values of the sensors calculated from the linear regression are given below. The responsivity is determined from the slope of the curve. The scale factor represents the inverse of the responsivity value.

| Serial # | Responsivity [mV/(W/cm$^2$)] | Scale factor [(W/cm$^2$)/mV] |
|---|---|---|
| 00000 | 3.084 | 0.324 |
| 11111 | 2.985 | 0.335 |
| 22222 | 2.924 | 0.342 |
| 33333 | 3.540 | 0.282 |
| 44444 | 3.612 | 0.277 |
| 55555 | 3.206 | 0.312 |

SAMPLE

## 4. Estimation of Uncertainty

Table 2 summarizes the calculated uncertainty at various stages of testing. First, the uncertainty accrued during the transfer of calibration to the transfer standard (ESR) from the primary radiometric standard is based on previous measurements and is expected to be 0.6 %. Second, uncertainties occur while transferring the ESR calibration to the heat flux sensor using the VTBB for broadband testing. The temperature of the VTBB during the test was stable to within 0.1 K of the set value. The output of ESR and the sensor were recorded for about 20 s to 30 s depending on the heat flux level. The standard deviation of the mean of the readings was found to be within about 0.2 % of the mean value at heat flux levels greater than 1 W/cm$^2$. The errors due to alignment are expected to be less than 0.4 %, since a fixed length gage block was used to locate the ESR and the gage in front of the VTBB.

Item 10 in Table 2 gives the results of uncertainty from several tests on the reference Schmidt-Boelter sensor in the same facility and using similar instrumentation and experimental setup. The uncertainty based on the long-term repeatability of the calibration of the reference sensor has been conservatively added in the calculation of the total relative expanded uncertainty for a coverage factor $k = 2$ [2].

## 5. General Information

The results of this calibration apply only to the sensors referenced in this report. This report shall not be reproduced, except in full, without the written approval of this laboratory.

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**References:**

[1] A. V. Murthy, B. K. Tsai, and C. E. Gibson, "Calibration of High Heat Flux Sensors at NIST," *J. Res. Natl. Inst. Stand. Technol.* **102**, 479-488 (1997).

[2] B. N. Taylor and C. E. Kuyatt, "Guidelines for Evaluating and Expressing the Uncertainty of the NIST Measurement Results," *NIST Technical Note* **1297** (2nd ed., 1994).

SAMPLE

**Table 1a**
**Heat Flux Calibration Results for sensors 00000, 11111 and 22222**

| | S/N 00000 | | S/N 11111 | | S/N 22222 | |
|---|---|---|---|---|---|---|
| **Blackbody Temperature [K]** | **Incident Flux [W/cm$^2$]** | **Sensor Output [mV]** | **Incident Flux [W/cm$^2$]** | **Sensor Output [mV]** | **Incident Flux [W/cm$^2$]** | **Sensor Output [mV]** |
| 298 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 1573 | 0.838 | 2.577 | 0.836 | 2.483 | 0.840 | 2.456 |
| 1773 | 1.290 | 3.978 | 1.283 | 3.817 | 1.290 | 3.769 |
| 1973 | 1.897 | 5.835 | 1.881 | 5.598 | 1.884 | 5.514 |
| 2123 | 2.453 | 7.556 | 2.457 | 7.319 | 2.454 | 7.176 |
| 2273 | 3.142 | 9.665 | 3.143 | 9.362 | 3.159 | 9.250 |
| 2353 | 3.568 | 10.974 | 3.576 | 10.668 | 3.574 | 10.443 |
| 2453 | 4.151 | 12.795 | 4.173 | 12.416 | 4.177 | 12.192 |
| 2553 | 4.812 | 14.862 | 4.833 | 14.439 | 4.831 | 14.134 |
| 2593 | | | 5.122 | 15.278 | 5.115 | 14.966 |
| 2603 | 5.180 | 15.959 | | | | |

| | **Linear regression results for calibration data** | | |
|---|---|---|---|
| | **S/N 00000** | **S/N 11111** | **S/N 22222** |
| Error MS | 2.35E-04 | 2.10E-04 | 1.01E-04 |
| Count | 10 | 10 | 10 |
| Intercept | -0.008 | -0.012 | 0.000 |
| Slope | 3.084 | 2.985 | 2.924 |
| R-square | 1.000 | 1.000 | 1.000 |

SAMPLE

**Table 1b**
**Heat Flux Calibration Results for sensors 33333, 44444 and 55555**

| | **S/N 33333** | | **S/N 44444** | | **S/N 55555** | |
|---|---|---|---|---|---|---|
| **Blackbody Temperature [K]** | **Incident Flux [W/cm$^2$]** | **Sensor Output [mV]** | **Incident Flux [W/cm$^2$]** | **Sensor Output [mV]** | **Incident Flux [W/cm$^2$]** | **Sensor Output [mV]** |
| 298 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 1573 | 0.834 | 2.947 | 0.838 | 2.992 | 0.855 | 2.713 |
| 1773 | 1.283 | 4.536 | 1.286 | 4.612 | 1.308 | 4.177 |
| 1973 | 1.874 | 6.646 | 1.894 | 6.795 | 1.908 | 6.100 |
| 2123 | 2.454 | 8.702 | 2.461 | 8.842 | 2.489 | 7.953 |
| 2273 | 3.154 | 11.162 | 3.163 | 11.378 | 3.188 | 10.212 |
| 2353 | 3.587 | 12.648 | 3.592 | 12.947 | 3.626 | 11.577 |
| 2453 | 4.166 | 14.753 | 4.201 | 15.121 | 4.216 | 13.502 |
| 2553 | 4.841 | 17.112 | 4.875 | 17.582 | 4.891 | 15.657 |
| 2593 | 5.116 | 18.145 | 5.161 | 18.643 | 5.162 | 16.557 |

| | **Linear regression results for calibration data** | | |
|---|---|---|---|
| | **S/N 33333** | **S/N 44444** | **S/N 55555** |
| Error MS | 5.75E-04 | 4.22E-04 | 2.84E-04 |
| Count | 10 | 10 | 10 |
| Intercept | -0.002 | -0.031 | -0.018 |
| Slope | 3.540 | 3.612 | 3.206 |
| R-square | 1.000 | 1.000 | 1.000 |

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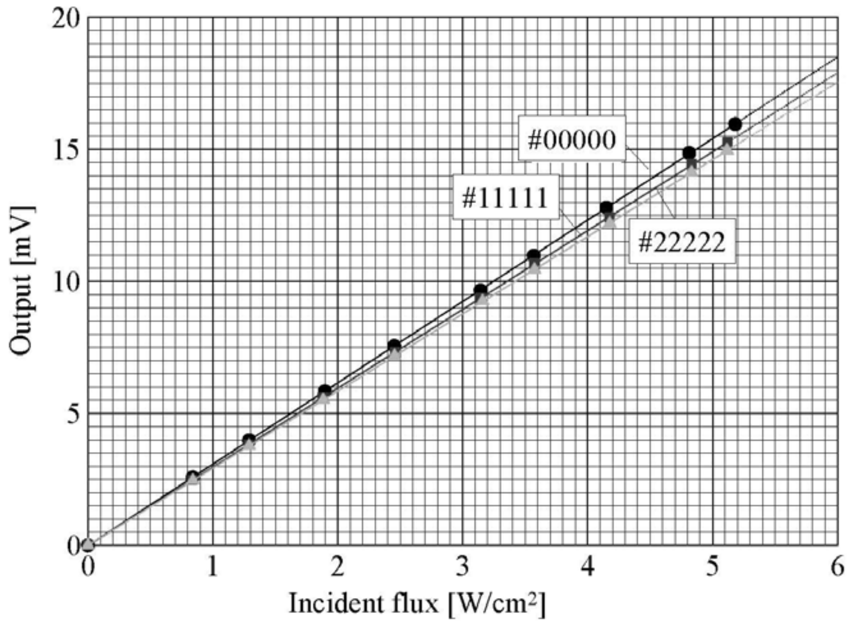


Figure 1a: Heat flux sensor calibration results for sensors 00000, 11111 and 22222

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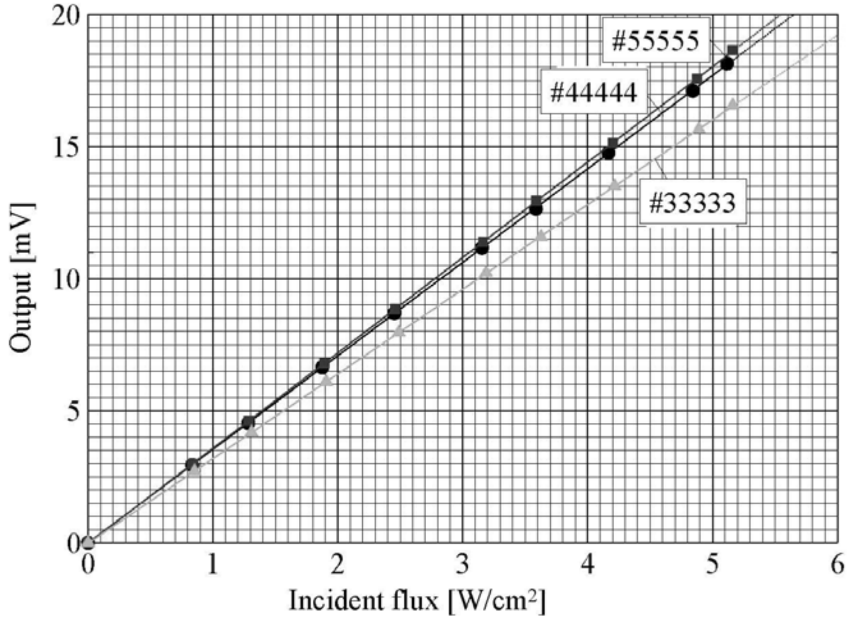


Figure 1b: Heat flux sensor calibration results for sensors 33333, 44444, and 55555

SAMPLE

**Table 2**
**Heat Flux Calibration Uncertainties**
**(Heat Flux Range 1 W/cm$^2$ to 5 W/cm$^2$)**

| Source of Uncertainty | Type | Uncertainty [%] |
|---|---|---|
| 1. Transfer standard ESR (Previous calibration) | B | 0.6 |
| 2. Blackbody temperature | B | 0.1 |
| 3. Blackbody emissivity | B | 0.0 |
| 4. Blackbody aperture uniformity | B | 0.0 |
| 5. ESR and sensor alignment in VTBB - linear | B | 0.4 |
| 6. ESR and sensor alignment in VTBB - angular | B | 0.1 |
| 7. Radiometer averaging effect | B | 0.1 |
| 8. ESR reading | A | 0.2 |
| 9. Sensor reading | A | 0.2 |
| 10. Repeat tests on a similar sensor | B | 0.7 |
| **Relative expanded uncertainty ($U = ku_c$)** | **$k = 1$** | **1.1** |
| **Relative expanded uncertainty ($U = ku_c$)** | **$k = 2$** | **2.1** |

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